Physical performance tests predict injury in National Collegiate Athletic Association athletes: a three-season prospective cohort study

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ABSTRACT

Background The ability to predict injury is difficult. Prior injury is the only risk factor that has been reported consistently in multiple research studies. Convenient and easy to perform, physical performance tests (PPTs) have great allure as prognostic factors.

Methods 11 PPTs were issued to 359 participants over the course of three seasons of National Collegiate Athletic Association Division I athletic competition. Injuries were monitored and reported in a centralised university tracking system. Exploratory factor analysis was performed in order to group the PPTs into constructs. The relationship between injury and these PPT-based constructs and other known predictors of injury was explored using univariate and multivariate regression.

Results PPTs clustered into five constructs: (1) active motion, (2) power, (3) hip stability, (4) flexibility and (5) motor control. When these five were placed into a multiple regression equation along with known risk factors (age, body mass index (BMI), gender, excessive flexibility and past injury), hip stability and active motion were predicted injury. In addition, motor control predicted non-traumatic injury. Past injury did not predict injury in the multivariate model.

Summary In college athletes, hip stability, active motion and motor control assessed through PPTs can be useful as part of preseason screening. These PPT-related constructs seem to have a mediating effect on the relationship between past injury and future injury. This study provides the rationale to test targeted interventions to address these limitations.

Clinical trial registration number NCT01804894.

INTRODUCTION

Injuries in the lower extremity in athletes are prevalent and costly. In one report, 7 million Americans were treated for sport-related injury.1 In another report,2 the cost of sport-related injuries seen in US emergency rooms alone during the same time period was $500 million annually. Sport-related injury is not just a US phenomenon. In an analysis of 1743 professional European football (soccer) players from 10 countries, players averaged 2 injuries per season from 2001 to 2012, most of which were to the lower extremity.3

A major goal in sports medicine and physiotherapy has been to identify those athletes who are at greater risk for injury. In theory, identifying athletes at greater risk of injury would allow targeted interventions that prevent injury. Previous injury is one of the strongest predictors of future injury in those with ankle sprains,4 hamstring strains,5,6 Achilles,6 and groin injuries.5,7

A recent systematic review examined factors predictive of lower extremity injuries.6 Some predictive factors are impairment-based (general laxity, quadriceps to hamstring strength ratio), some demographic in nature (height, age, body mass index (BMI)), and some biomechanical in nature (increased knee abduction moment). However, only one physical performance test (PPT) predicted injury, the modified Star Excursion Balance Test (SEBT), and only in high school basketball players.3

PPTs are multijoint, multisystem assessments that require the athlete to physically perform a task that represents some construct of athletic function such as power, stability or anaerobic capacity. The advantage of PPTs is that these tests are easy to administer across settings (court, field, laboratory or clinic), do not require expensive equipment (frequently a stopwatch or tape measure) and are easy to administer and interpret.10 Owing to these attributes, PPTs are ubiquitous throughout the sporting world and issued by physicians, physiotherapists, athletic trainers, strength and conditioning specialists and coaches during preseason screens with hopes of detecting anomalies that might predict potential injury.

Recently, two systematic reviews have cast doubt on the ability of PPTs to predict injury.10,11 Both reviews outlined the complexity of predicting an injury over a period of time and the challenges of assuming utility associated with prescreening for injury risk. In part, the authors reported that although PPTs are designed to replicate functional activities necessary in sports such as flexibility, motor control and strength, the tools, used individually, seem to lack the ability to fully assess the complex components associated with injury risk. In addition, other have found that singular predictive measures may not be comprehensive enough to address the multitude of injury types and the variations in individual characteristics of those studied.12-15

In principle, constructs that are protective or risk factors for an injury are most likely multidimensional, involving complexities beyond those of a single PPT. Consequently, the purpose of this study was to model PPTs into similar constructs to improve the multidimensional nature of these tools. Therefore, our primary aim was to identify the prognostic ability of PPTs in a large sample of competitive athletes. We then hope to identify the prognostic ability of the newly created PPT constructs in a prospective effectiveness study involving competitive athletes.
METHODS
Study design and injury definition
The study was a prospective, longitudinal cohort design involving a baseline assessment phase and longitudinal reassessment of injury over a 3-year time span. Injury was defined as an event that caused the athlete to seek care from the members of the university-sponsored healthcare team. This definition did not include illness. At the end of each season, injury records were reviewed and injuries were reclassified into traumatic or nontraumatic. Traumatic injuries included sprains, fractures, concussions, contusions, dislocations and tears. Non-traumatic injuries included strains, tendonitis/tendinosis, spasm, degeneration and bursitis. If there was any confusion about the injury classification, the athlete’s medical record was consulted to confirm. Each season/year was treated as a separate encounter so that some athletes represent multiple data points. This method allowed for close and accurate monitoring of previous injury.

Participant recruitment
All participants in this university institutional review board (IRB)-approved study were National Collegiate Athletic Association (NCAA) division one (D1) athletes from the same university. The university has eight sports including soccer, lacrosse, basketball, volleyball, cross country, track and field, golf and baseball. The head coach for each sport was asked if his or her players would participate in a preseason screening testing session consisting of 11 PPTs. Coaches and players had the right to refuse participation so the final sample was a sample of convenience that did not include men’s soccer players or golfers.

Data collection
After signing a letter of informed consent, participants completed a demographics questionnaire and were allowed whatever warm-up they felt was appropriate before testing. The warm-up was not standardised. Participants then chose one of 11 testing stations, each representing a different PPT. As this was a study of effectiveness, the test order was not randomised and the experience of each individual conducting the PPT varied. Regardless of experience, each examiner was given a copy of all PPTs that consisted of a written description of the tests, the scoring of the tests and a photograph of the tests. Each examiner practiced the test under the guidance of an experienced examiner before testing athletes. The reliability of these tests as performed throughout the study has been established previously.16 The tests are presented in online supplementary table S1. Injury and treatment for all athletes was monitored and stored in a central database. No attempt was made to change the athletes’ strength training, practice patterns or competition as a result of preseason testing.

Modelling of PPTs
The purpose of this study was to model PPTs into similar constructs in order to improve the multidimensionality of these tools. Since the measurement properties and ability of PPTs to predict injury are largely unknown,10 an exploratory factor analysis (EFA) was performed to combine like-type PPTs into similar, latent (not easily observable) constructs.11 An EFA is used to identify the number of latent constructs within a set of variables without a preconceived assumption of the number of latent constructs or the structure of the variables examined. EFA is an efficient mechanism for variable reduction and allows creation of new variables based on the composition of those included in the latent construct through modelling.

Prior to EFA, each PPT (predictor variable) was examined for linearity of effect and recoded as necessary. Continuous data were examined using both the Kolmogorov-Smirnov (K-S) test and quantile-quantile (Q-Q) plots. Categorical data were examined through use of frequencies. If the data were not normally distributed or had an unbalanced representation, the predictor variables were re-categorised using the ‘visual binning’ command in SPSS for Windows, V.22 (IBM Corp, Armonk, New York, USA) which produces a histogram of data. After the PPT variables were re-categorised (binned), their suitability for factor analysis was examined through the use of the Kaplin-Meyer-Olkin (KMO) measure of sampling adequacy, Bartlett’s test of sphericity and an anti-image correlation matrix. The KMO should be close to 1 in order to proceed with factor analysis. Bartlett’s test of sphericity compares the study matrix to an identity matrix (one with all 1 s on the diagonal). A significant (p<0.05) Bartlett’s test indicates variables are appropriate for factor analysis. The anti-image correlation matrix is the negative of the partial correlations and reports KMO statistics for each factor along the diagonal of the matrix and each factor should have a KMO above 0.50 to be acceptable.18

Next, factor extraction and rotation of maintained factors was completed. Those PPT factors found suitable for factor analysis were examined via a factor analysis with varimax rotation.19 Varimax is an orthogonal rotation performed for the purposes of uncovering a more meaningful pattern of item factor loadings and to minimise the complexity of the loadings.20 Since the objective was to further delineate predictive constructs associated with injury risk, those latent constructs with eigenvalues greater than 1.0 were retained.

Determining appropriate number of observations per variable
We determined the appropriate number of observations per variable by using the recommendations of Hosmer and Lemeshow.21 For simple univariate multinomial or logistic regression, Hosmer and Lemeshow21 have recommended a minimum observation-to-variable ratio of 10, but cautioned that a number this low will likely overfit a model. That said, on removal of variables that demonstrated multicollinearity we adopted their preferred observation-to-variable ratio of 20 to 1 for the multivariate modelling. With these recommendations, the maximum multivariate model would include approximately 15 associative variables.

Statistical analysis
Variables selected for presentation of descriptive statistics, included age, BMI, gender and sport. For age and body mass, the number of participants, minimum and maximum values, mean and SD were calculated. For gender, number and percentage of participants in each category were calculated. The percentage of athletes participating in each sport was also calculated.

Univariate and multivariate regression modelling was used to predict the likelihood of injury during the follow-up period. We adopted the concept of explanatory modelling and assumed that the statistical associational assessment was testing for causal relationships. Explanatory modelling involves building a bridge between theoretical constructs (PPT latent constructs) and observable measurements (incident injury) using statistical associational findings, previous literature for justification and clinical sensibility.22

Prior to regression analysis, the retained variables were then evaluated for co-linearity using a correlation matrix for the newly created variables. If two variables were correlated
significantly (>0.70), one was eliminated prior to univariate analysis. The univariate analysis was conducted with the five new variables/constructs from the factor analysis, and five additional variables found, in prior research, to be risk factors for injuries: past injury, gender, age, BMI and hyper-flexibility as represented by the Beighton score. The univariate analysis was completed three times: once with injury, once with non-traumatic injury and once with traumatic injury as the dependent variable. Variables with p values <0.25) were retained for multivariate analysis.

The multivariate analysis, hierarchical regression, was conducted with the retained variables from the univariate analysis again using injury, non-traumatic injury and traumatic injury each as the dependent variable. For each univariate analysis, individual p values, ORs and 95% CIs and Nagelkerke values were reported. A Nagelkerke is a pseudo R square measure that investigates the usefulness of the model. The value is similar in concept to the coefficient of determination (R^2) in linear regression. The R^2 statistics do not measure the goodness of fit of the model but indicate how useful the explanatory variables are in predicting the response variable and can be referred to as measures of effect size. All statistical analysis was performed using SPSS Statistics for Windows, V.22.0 (IBM Corp, Armonk, New York, USA).

**RESULTS**

**Sample description**

Descriptive statistics are presented in table 1.

**Exploratory factor analysis findings**

Overall, the KMO (0.801) and Bartlett’s test (0.000) found the 11 PPT variables appropriate for factor analysis. However, examination of the individual KMO for each test revealed the ‘hamstring cont (binned)’ variable, representing the Nordic hamstring test, to have a value of 0.411 making this variable inappropriate for inclusion in the factor analysis. Ten PPTs representing 17 variables (many PPTs had both a left and right component which represented 2 variables) entered the factor analysis. Analysis revealed five distinct constructs representing active motion, power, hip stability, flexibility and motor control (table 2).

**Assessment of collinearity**

Each of the five new constructs/variables was entered into a correlation matrix to check for co-linearity. None of the new variables were correlated at the 0.70 level or above clearing each for univariate analysis.

**Univariate and multivariate analysis**

The single independent variables that were retained (p<0.25) varied based on the dependent variable; however, when qualifying univariates were entered into the multivariate models, two models emerged:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Component</th>
<th>1 Active motion</th>
<th>2 Hip stability</th>
<th>3 Power</th>
<th>4 Flexibility</th>
<th>5 Motor control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side plank hip ABD—left</td>
<td></td>
<td>0.831</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side plank hip ABD—right</td>
<td></td>
<td>0.820</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side plank hip ADD—left</td>
<td></td>
<td>0.763</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side plank hip ADD—right</td>
<td></td>
<td>0.783</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triple hop—left</td>
<td></td>
<td></td>
<td>0.862</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triple hop—right</td>
<td></td>
<td></td>
<td>0.861</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vertical jump</td>
<td></td>
<td></td>
<td></td>
<td>0.770</td>
<td></td>
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</tr>
<tr>
<td>In-line lunge—left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.520</td>
<td></td>
</tr>
<tr>
<td>In-line lunge—right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.910</td>
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<tr>
<td>Lateral lunge—left</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Lateral lunge—right</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Full unloaded squat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Single leg squat—left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single leg squat—right</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downward dog</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active straight leg raise—left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active straight leg raise—right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Extraction method, exploratory factor analysis.
Rotation method, Varimax with Kaiser Normalisation.
ABD, abduction; ADD, adduction.
1. When lower extremity injury was examined as a dichotomous independent variable, the retained variables were age, gender, past injury, active motion, hip stability and motor control (table 3). When these six variables were placed in the multivariate equation, higher scores on active motion and hip stability demonstrated a protective effect toward injury (see online supplementary table S2). More specifically, better performance on active motion and hip stability were protective of injury. When the regression model was repeated with just these two variables, the model had a Nagelkerke $R^2$ of 0.167.

2. When lower extremity non-traumatic injury was examined as a dichotomous independent variable, the significant univariate variables were age, gender, past injury, active motion, hip stability and motor control (table 3). When these six variables were placed in the multivariate equation, higher scores on motor control demonstrated a protective effect toward injury (table 3).

DISCUSSION

Predicting a complex event such as injury is difficult and contributing factors are likely multifactorial.\(^\text{12–15}\) We selected 11 tests with the concept that each would contribute to key elements of athletic movement like hip stability, eccentric hamstring strength, flexibility, active motion, power, movement symmetry and motor control. The thought was that poor performance on these tests would likely set the stage for injury. Our choices were based on previous work,\(^\text{22–26}\) but some were based on clinical reasoning and experience.\(^\text{22}\) For example, the hip abduction test in side plank, novel to our study, was thought to assess the activity of all of the muscles that prevent the knee-damaging cascade of poor trunk/hip control producing hip adduction, femoral internal rotation and functional knee valgus.

To improve the multidimensionality of the PPTs in our study, we undertook factor analysis was undertaken. Through factor analysis, we delineated five clear, distinct constructs that require greater investigation in future studies as the components of a preseason screen: hip stability, active motion, flexibility, power and motor control. Interestingly, some of the new constructs appeared protective of injury whereas past injury did not.

Unlike previous studies specifically examining lower extremity injury, past injury was not a predictor of future injury.\(^\text{4,53}\) These findings are both puzzling and exciting. Puzzling, since previous studies have demonstrated that past injury was a clear predictor of future injury in the lower extremity.\(^\text{4,53}\) Exciting because only one other study has described the ability of a PPT to predict injury and only in high school basketball players.\(^\text{9}\)

The reasons behind the lack of predictive validity of past injury are unclear but differences between our study and past work addressing lower extremity injury may explain this apparent anomaly. Hägglund et al\(^\text{5,32}\) conducted two studies that examined lower extremity injury in elite soccer players. One study\(^\text{32}\) examined exclusively lower extremity muscle injuries in soccer players and had a far greater sample size (1401 players) collected over a greater time period (9 years) than our study. Past injury may have become a risk factor in our study with a larger sample size or with athletes followed over a longer period of time. Another explanation for the divergent findings might be that the sample populations differed sufficiently to warrant different findings. Both Hägglund et al\(^\text{3,32}\) studies examined a different patient population than this current study and defined injury differently. Their studies included male, elite soccer players exclusively. Our study contained male (43%) and female (57%) collegiate athletes from multiple sports including soccer. It could be that past injury does not predict future injury in every athletic population. In addition, our definition of injury differed. The Hägglund et al\(^\text{3,32}\) studies defined injuries by time lost from participation whereas our study defined injury as those events precipitating athletes to receive documented treatment from one of our healthcare professionals (illnesses excluded). There is no universally accepted definition of injury currently.\(^\text{33}\)

Finally, our study included physical performance tests, which the Hägglund et al\(^\text{3,32}\) studies did not. The presence of these tests in our model may have eliminated past injury as a significant predictor. In the univariate analysis of both injury and non-traumatic injury, past injury was a significant predictor (p<0.001). However, in the multivariate analysis, past injury did not predict future injury. Therefore, our PPT-related constructs likely mediated or confounded the relationship between past injury and both injury and non-traumatic injury. If, in fact, motor control mediates the relationship between past injury and overuse injury and active motion and hip stability mediate the relationship between past injury and injury as this paper shows, then our findings present great rehabilitation possibilities.

The multivariate analysis showed that in our population of NCAA Division I athletes, hip stability and active motion are important constructs that predict injury and that these constructs can be investigated rather efficiently through PPTs. Our construct of hip stability consisted of two tests: side plank hip adduction and side plank hip abduction. Our construct of active motion consisted of forward lunge (left and right leg) and lateral lunge (left and right leg). In addition, our construct of motor control, which consisted of the single leg squat test for the left and right lower extremity and the unloaded full squat scored on a 0–5 scale, predicted non-traumatic injuries. Better performance on these tools demonstrated a protective effect toward injury: active motion was associated with a 49% decrease in the odds for an injury; hip stability was associated with a 56% decrease in odds for an injury; and motor control was associated with a 59% decrease in the odds for a non-traumatic injury. We are not aware of another study that has established this relationship between PPTs and non-traumatic injury. The model for traumatic injury was not significant. If the results of this study are combined with previous work,\(^\text{4}\) then it would seem that a short list of PPTs appropriate for preseason screening is emerging. Some caution should be exercised since

### Table 3 Multivariate hierarchical binary logistic regression for lower extremity injury in athletes

<table>
<thead>
<tr>
<th>Variable</th>
<th>OR (95% CI)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active motion no or yes</td>
<td>0.511 (0.263 to 0.991)</td>
<td>0.047</td>
</tr>
<tr>
<td>Hip stability</td>
<td>0.436 (0.200 to 0.953)</td>
<td>0.037</td>
</tr>
<tr>
<td>Past injury</td>
<td>0.367 (0.090 to 1.489)</td>
<td>0.161</td>
</tr>
<tr>
<td>Gender</td>
<td>0.089 (0.199 to 5.955)</td>
<td>0.922</td>
</tr>
<tr>
<td>Age</td>
<td>0.101 (0.471 to 2.164)</td>
<td>0.980</td>
</tr>
<tr>
<td>Motor control</td>
<td>0.502 (0.200 to 1.261)</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Model 1—lower extremity injury yes or no

Model 2—non-traumatic injury yes or no

Motor control | 0.407 (0.181 to 0.914) | 0.030 |
Active motion | 0.608 (0.330 to 1.120) | 0.111 |
Hip stability | 0.847 (0.462 to 1.556) | 0.593 |
Past injury | 0.516 (0.145 to 1.843) | 0.516 |
Gender | 1.742 (0.443 to 6.853) | 0.427 |
Age | 1.104 (0.577 to 2.111) | 0.765 |

Variables retained for multiple regression in bold.
the modified SEBT was studied only once and only in high school basketball players, and with regard to our current study, there are some limitations to factor analysis.

Limitations

By definition, exploratory factor analysis is designed to allow exploration of future hypotheses by creating hypothetical statistical constructs. As such, these factors do not allow a direct clinical translation. Therefore, although we established hip stability and active motion as an important predictors of injury and motor control as an important predictor of non-traumatic injury, we do not know if our novel hip abduction and adduction tests or the single leg squat test themselves predict injury nor do we have an appreciation of the exact cut point that is most meaningful for these PPTs.

Also, the current study is a study of effectiveness, designed to examine the predictive ability of PPTs as they are likely assessed in clinical practice with a large number of athletes tested in a limited amount of time. By definition, a study of effectiveness has a less rigid design. Therefore, the possibility exists that examiners of different experience impacted the reliability of the tests. However, each examiner received training from a more experienced examiner and was given a copy of all PPTs that consisted of a written description of the tests, the scoring of the tests and a photograph of the tests. In addition, we have previously established the reliability of our tests under these conditions.

A final limitation is that the scoring system that we used for the qualitatively scored tests (squat, single leg squat, downward dog and active straight leg raise) has not been validated. These were predominantly novel tests with no universally accepted scoring system, although the single leg squat as well as the active straight leg raise and unloaded full squat have had scoring systems proposed.

CONCLUSIONS

Factor analysis revealed five distinct constructs that bear further investigation: active motion, power, hip stability, flexibility and motor control. PPTs that represent these constructs should be investigated as part of a battery of tests comprising a preseason screen. Further, as assessed by PPTs, active motion and hip stability seem to predict lower extremity injury and motor control seems to predict non-traumatic injury in athletes. Further investigation is required to determine the ideal cut point of some of our novel tests of (side plank hip abduction and side plank hip adduction; forward and lateral lunge) and some often used tests with unique scoring systems (single leg squat and unloaded full squat tests).

What are new findings?

- Factor analysis revealed five distinct constructs that bear further investigation as preseason screens: active motion, power, hip stability, flexibility and motor control.
- The constructs of active motion and hip stability seem to predict lower extremity injury in athletes.
- The construct of motor control seems to predict non-traumatic injury in athletes.
- The physical performance test (PPT) that comprise the variables of active motion, hip stability and motor control seem to modify the relationship of past injury to future injury.

How might it impact on clinical practice in the future?

- A preseason screen composed of easy-to-perform tests that predict lower extremity injury and represent multiple constructs is of value.
- Some novel tests (side plank hip abduction, side plank hip adduction, downward dog) seem to have value and require further clinical testing.
- Knowing that PPT-composed constructs might mediate the effect of past injury on future injury should lead clinicians to investigate whether interventions based on deficits in these tests might alter the rate of reinjury in athletes.

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Contributors EJH developed and executed the study, performed the statistical analysis and wrote the initial draft of the manuscript. SM, CB and GDB edited the manuscript. JTD collected data, provided injury surveillance and edited the manuscript. IB performed the statistical analysis. CC planned and consulted on the statistical analysis and edited the manuscript.

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Data sharing statement The authors are happy to share with receipt of a written request by the corresponding author.

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